High-Resolution Measurement-Based Phase-Resolved Prediction of Ocean Wavefields

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LONG-TERM GOAL

Given remote and direct physical measurements of a realistic ocean wavefield, obtain a high-resolution description of the wavefield by integrating the measurements with phase-resolved wave prediction model including realistic environmental effects such as wind forcing and wave breaking dissipation. Inform and guide the measurements necessary for achieving this reconstruction and address the validity, accuracy and limitations of such wavefield reconstructions.

OBJECTIVES

The specific scientific and technical objectives are to obtain:

1. Development of a phase-resolved, deterministic prediction capability for nonlinear wavefield reconstruction and evolution at intermediate scale (O(1) ~ O(10)km per dimension) using ship-mounted radar wave measurements
2. Incorporation and evaluation of physics-based wind-forcing and wave-breaking models that are developed/calibrated/validated based on simulations and measurements
3. Characterization and quantification of uncertainty and incompleteness in wave sensing and sensed data
4. Direct comparison between quantitative field/laboratory measurements and nonlinear wavefield reconstruction and prediction

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5. Development of a theoretical/computational framework that can guide deployment of wave sensing systems and data interpretation

APPROACH

We develop and apply a comprehensive deterministic model for intermediate scale (up to O(10)km per dimension) ocean wave environment prediction by integrating whole-field and multiple-point measurements of the wave and atmospheric environment with simulation-based reconstruction of the wavefield. The wave reconstruction is based on phase-resolved **s**imulation of **n**onlinear **o**cean **w**ave (SNOW) dynamics, and utilizes hybrid (from different types of sensors) measurements that may contain noise, uncertainty and gaps. The simulations also incorporate physics-based wind forcing and wave-breaking dissipation models, which are developed/validated/calibrated based on field/laboratory measurements.

Nonlinear wavefield reconstruction is based on an iterative optimization approach using multilevel phase-resolved wave evolution models of different nonlinearity orders. Specifically, for low-level optimization which is sufficient for mild waves, the theoretical linear and second-order Stokes solutions are used. For high-level optimization which is required for moderately steep waves, an efficient nonlinear wave simulation model (SNOW) based on the high-order spectral method is employed. Once the wavefield is reconstructed, its future evolution is given by wave evolution models using the reconstructed wavefield as an initial condition (Wu 2004; Yue 2008). In wave modeling, wind forcing is included through a pressure distribution on the free surface and wave-breaking dissipation is considered by an effective low-pass filter in spectral space. Other physical effects such as those due to the presence of current and finite depth can also be directly considered in wave modeling.

WORK COMPLETED

We focus on validation and performance tests of deterministic wave reconstruction capability using HiRes field measurements of realistic ocean waves. Specifically, the following work is completed:

- **Further development and improvement of nonlinear wave reconstruction and forecasting capability:** We extend the reconstruction and forecasting capability for hybrid discrete point and whole-field radar data (and ATM) data. The effects of surface current and finite depth are also included. In addition, we develop an effective algorithm with the incorporation of nonlinear phase-resolved wave reconstruction to improve the resolution of radar inversion data.

- **Validation, calibration and direct comparison with HiRes 2010 field measurements:** The developed wave reconstruction/forecasting capability is applied to obtain direct comparisons with HiRes 2010 field measurements. The performance of wave measurements and model predictions are assessed. Specifically,
    - For SPROUL-based radar data on June 7th and 14^{th,} the model predictions are compared with the on-site buoy data and the radar data not used in reconstruction
    - For FLIP-based radar data on June 11th and 18th, the model predictions are compared with the radar data not used in reconstruction, and the effect of wave spreading angle on radar measurements and wave forecasting performance is studied

- For ATM data on June 8th, the model predictions are compared with ATM data.
- Based on combined SPROUL and FLIP radar measurements, large-scale wavefields are reconstructed and their future evolutions are forecasted. The predicted wavefields are cross-validated with independent ATM measurements and Datawell buoy data.

RESULTS

To assess the performance of wave measurements and model predictions, direct comparisons between wave model predictions and HiRes 2010 field measurements are performed. The comparisons indicate that phase-resolved reconstruction and forecasting of realistic ocean wave-fields can be achieved by our wave prediction model and (ship-mounted and FLIP-mounted) non-coherence marine radar sensed data. The resolution of the reconstructed and forecasted wave-field depends critically on the accuracy of sensed wave data, which is largely affected by radar-data inversion algorithm and measurements of the platform motion.

In particular, based on combined SPROUL-based and FLIP-based radar sensed wave data (on June 8, 2010), we obtain a reconstruction of large-scale short-crested wavefields in a domain of ~20 km $\times$ 20 km. The predicted wavefield evolution is compared with the independent ATM measurement and Datawell buoy data. It is found that the wave spectrum is well predicted while the predicted phased-resolved sea surface has a ~40% correlation with the ATM measurement.

Figure 1 illustrates a sample instantaneous sea surface of the reconstructed wavefield, in which the regions of the wavefield sensed by FLIP-mounted and SPROUL-mounted radars and the locations of Datawell buoys are indicated. The mild sea has a significant wave height of 3.1m and a peak period of 8s. The wind speed is about 13 m/s. Figure 2 shows the direct comparisons between the reconstructed phase-resolved wavefield with the ATM measurement, with the correlation coefficient reached ~40%. Figure 3 shows the comparisons of the time varying wave elevations between the model prediction and the buoy measurements at three locations. The comparison of frequency spectra is also made in figure 3. Though the results are quite encouraging, more comparisons between model prediction and HiRes field measurements need to be performed for further assessment of phase-resolved ocean wave sensing and model prediction capabilities.

IMPACT/APPLICATIONS

Advances in large-scale nonlinear wave simulations and ocean wave sensing have recently made it possible to obtain phase-resolved high-resolution reconstruction and forecast of nonlinear ocean wavefields based on direct sensing of the waves. Such a capability will significantly improve ocean-surface sensing measurements and deployment, and data assimilation and interpretation, by providing a comprehensive wave-resolved computational framework. Another important potential application of this is to greatly increase the operational envelopes and survivability of naval ships by integration of such capability with ship-motion prediction and control tools.

RELATED PROJECTS

The present project is related to the project entitled “Fundamental Research to Support Direct Phase-Resolved Simulation of Nonlinear Ocean Wavefield Evolution” (N00014-10-1-069). The present project focuses on the application of the deterministic wave reconstruction/prediction capability to

realistic ocean environment while the related project focuses on the understanding of fundamental algorithms and accuracies/reliabilities of deterministic wave reconstruction and forecasting based on point and/or whole field wave measurements.

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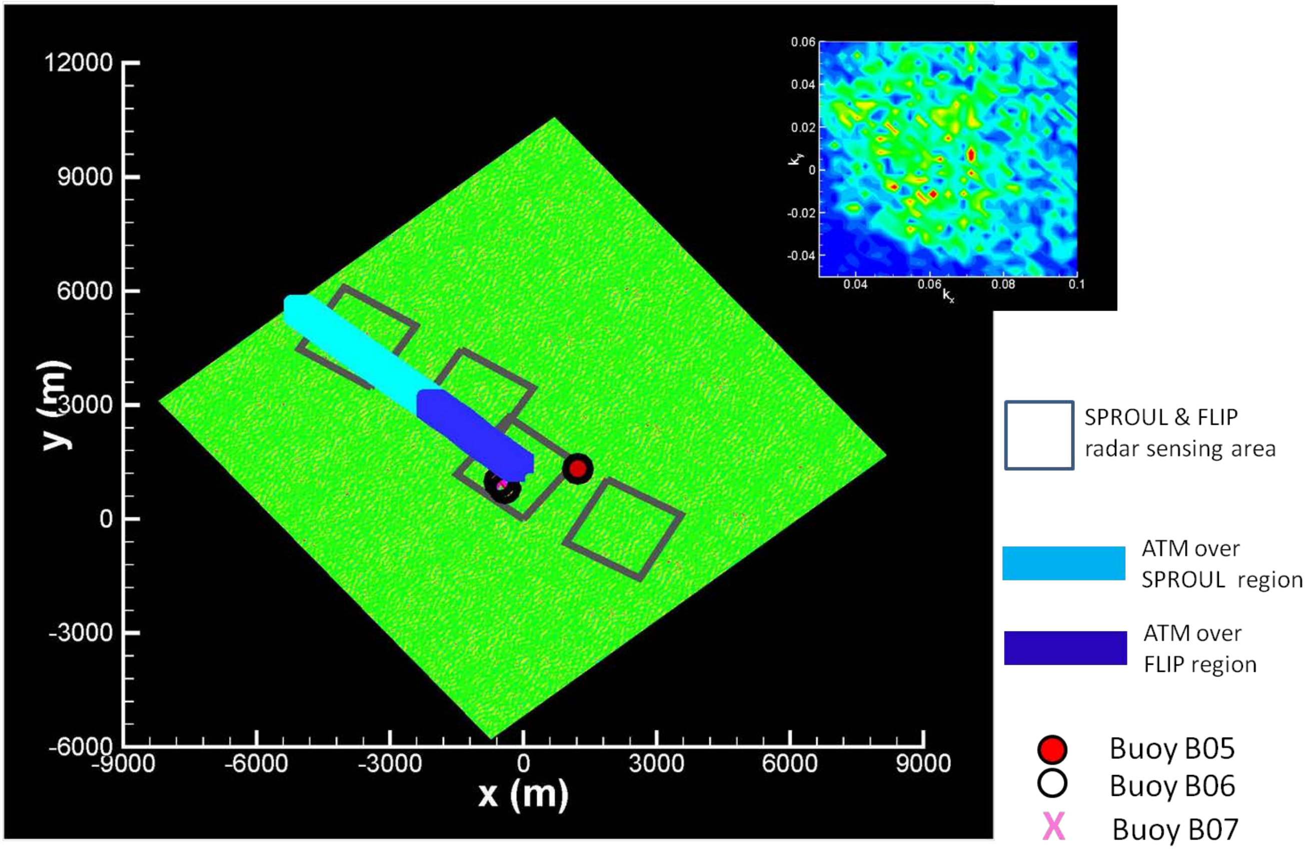

Figure 1. Reconstructed wavefield of ~20 km $\times$ 20 km based on combined SPROUL-based and FLIP-based marine radar measurements on June 8, 2010. The reconstructed wavefield is to be compared with the independent ATM and buoy measurements. The regions sensed by SPROUL-based and FLIP-based radars and ATM and the locations of buoys are indicated. The sub-panel at the right-up corner is the wavenumber spectrum of the wavefield.

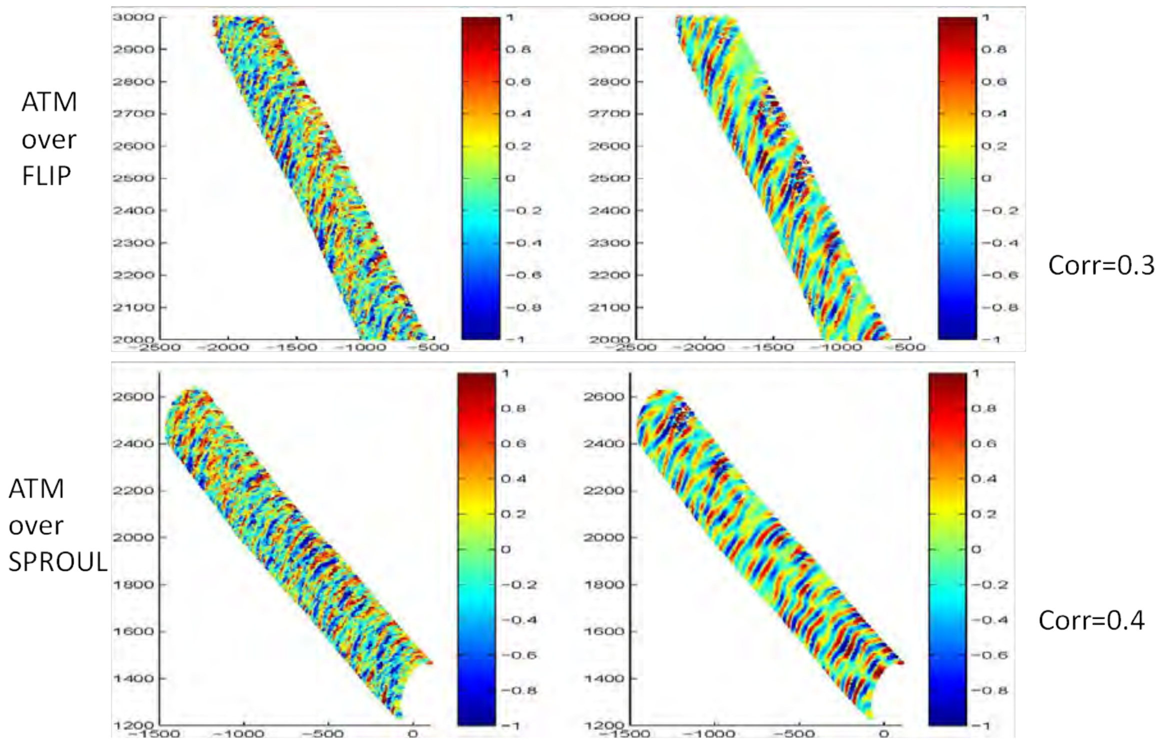

Figure 2. Direct comparisons between the reconstructed wavefield (right panels) with the independent ATM measurements (left panels) in the regions covered by FLIP- and SPROUL-based radar sensing.

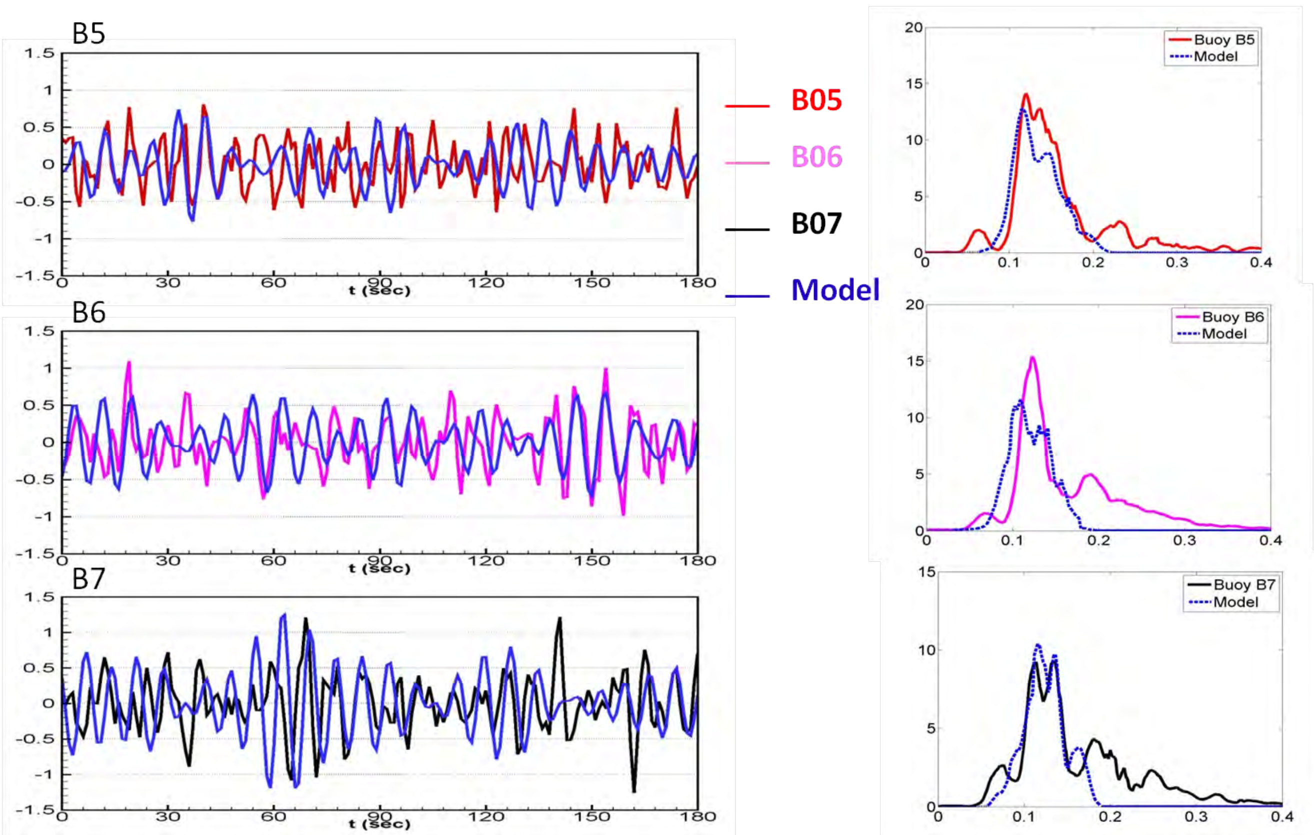

Figure 3. Direct comparisons of time history of wave elevations (left panels) and frequency spectra (right panels) between the model prediction and independent buoy measurements.